DOCUMENT RESUME

ED 180 776 SE 029 405

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TITLE A Basic Problem Solving Skill Not Mastered in the Introductory Calculus Based Physics Course.
PUB DATE Oct 79
NOTE 19p.: Not available in hard copy due to copyright restrictions: Contains numerous light and broken type

EDRS PRICE MF01 Plus Postage. PC Not Available from EDRS.
DESCRIPTORS *College Science: *Educational Research: Generalization: Higher Education: *Mastery Learning: *Physics: Physics Instruction: *Problem Solving: Skills

ABSTRACT

It is conjectured that some skill entering into problem solving in physics courses might be responsible for making these courses so difficult. This might be the case if one or more basic problem-solving skills could not be mastered in the time and practice available. In order to test this hypothesis, a model of the way in which students solve problems is proposed. The model has six observable steps based on the structure of the solution: each step is assumed to correspond to a basic skill. For a fairly typical group of students in an introductory calculus-based physics course, it was found that all but two of these skills are learned as well as might be expected. The skills not learned at mastery levels are the recognition of laws that apply and the substitution of all definitions into laws. The later skill is learned rapidly and might be improved upon by additional materials, but the former skill is learned too gradually for substantial improvement to come about through practice. Thus the skill of recognizing which laws apply is likely to be a source of great difficulty preventing an unattainable goal of instruction in its mastery in problem solving. (Author/MK)

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A BASIC PROBLEM SOLVING SKILL NOT MASTERED IN THE INTRODUCTORY CALCULUS BASED PHYSICS COURSE

by
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INTRODUCTION

Physics teaching has come under attack in recent years. Some critics feel there must be something wrong with physics teaching due to the dissatisfaction of the students, shown by their low grades and high drop out rates. Some physics teachers [1,2] are of the opinion that it is lack of student preparation and poor study habits that are responsible for such poor performance. Whatever the cause, declining enrollments are evidence of dissatisfaction and frustration among students taking physics courses. These declines were noted as beginning at the turn of the century by Casewell[3] who observed a decline relative to the other sciences. Since 1955 the decline has been even more noticible according to a 1979 editorial by Gerhart.[4]

These declines are probably due to the impression of students that physics is a hard subject. It is this question that one should investigate: What makes the learning of physics so hard? It cannot be simply the lack of good work habits. "Even some of the students who find physics interesting and fascinating, and do well in physics courses, admit that physics is a hard subject,"[5] according to Behl. In order to identify what makes physics courses hard, it has been recommended that one investigate processes as well as content,[6] the hierarchial structure of physics,[7] and the reactions of students to the materials of physics.[8] However, Casewell, nearly fifty years ago put the blame specifically on problem solving as an end in itself. Once physics teaching departed from teaching only illustrative examples, it opened the door to what Casewell called a "cancer in the body of physics."[9]

RESEARCH PROBLEM

This study plans to identify and then measure the learning of basic problem solving skills as they occur in courses whose problems go beyond illustrative examples. A calculus based introductory physics course for students of science and engineering is likely to be a good example of this kind of problem solving. Measuring performance of these skills on the examination questions will identify which of the skills prove to be "too hard", i.e. not capable of being mastered. If any skills are found to be too hard to be mastered, then Casewell might be correct in selecting problem solving as the cause of the dissatisfaction and the declining enrollments.

PROBLEM SOLVING

First one might ask: How do students solve physics problems? We do not know, specifically, the answer to that question, but we do know the answer to how students solve problems in geometry according to Krutetskii.[10]

The work reported by Krutetskii concerns basic research done by Slavskaya under the guidance of Rubinstein with both adults and senior pupils. The results indicate that students are able to recognize similarities in new problems by comparing them, not necessarily consciously, with problems previously worked. They then generalize both problems, or parts of both problems to the point where each is a specific instance of the same general problem.

Another Soviet study by Shchedrovitskii and Yakobson[11] indicates that one of the things pupils generalize from similar problems is a rule for handling both instances. From the problem 5 + 7 = ? they might generalize a counting rule to add the two numbers together. Thus when they see the problem 12 - 7 = ? they might just answer 19 rather than 5 and be quite adamant about their answer. Similarly an introductory physics student dealing with the problem of two strings holding up a weight might first write correctly that $T_{1x} = T_{2x}$ and then apply the same rule to the vertical components to write incorrectly that $T_{1y} = T_{2y}$.

When dealing with complex problems, solutions are still found by the recognition of similarities and the generalization of rules. According to Newell and Simon [12] recognition is the universal method of problem solving. The complex problem is first broken down into parts which can be recognised as similar to previously solved problems. Then whatever rule the student has generalized can be applied to each part.

Larkin [13] has drawn attention to the logical structure of physics problems and that this structure includes the selection of a law as a major premise and the identification of suitable definitions as minor premises. From these the answer is found by substitution and mathematical manipulation. The complete list of logical steps is given in Table 1.

From these findings the following two assumptions will be made:
(1) The student must recognize the similarities in the logical structure of the solutions to the problems, not just any similarities whatsoever.
(2) The student must recall and apply rules of sufficient generality to work each part of the problem, not just the special case formulae that worked in the more elementary problems.

Table 1

Steps in the Derivation of Equations in Physics Problems

(1)	Identify the known and unknown quantities from what's given.
(2)	Translate what's given and wanted into symbols, a sketch.
(3)	Recognise the underlying laws that apply (major premises).
(4)	Identify the relevant definitions (minor premises).
(5)	Substitute the defining equations into the law or laws.
(5')	Solve the equation using symbols not numbers.

It will be further assumed that (5) each step in the derivation of suitable equations is a basic problem solving skill. Thus these steps in the logical structure of the solutions will serve as the skills needing to be measured. A breakdown of a sample problem in Table 2 following these steps will illustrate how the measurements might be carried out.

Problem solving in physics is then assumed to proceed by the recognition of similarities between the present and previous problems so that the student can complete each of the logically necessary steps, not necessarily in just that order, but eventually in order to complete the correct problem as expected. Each step is assumed to be a specific skill in using the specific content of physics. That the skill is not learned in some general way applicable to new content is discussed elsewhere.[14]

Table 2

Illustrative Problem Broken into Logical Steps

A body has a mass m, a radius r, and a moment of inertia about the center of $I = kmr^2$. It starts from rest at a height h above the bottom of a round bowl of radius R, where $R \gg r$, and rolls without slipping. From energy considerations, find the velocity, v_b, of this body at the bottom of the bowl, point b. Obtain v_b in terms of h,k, and whatever else.	
(1)	STATE "find the velocity v_b"
(2)	STATE $v_b = ?$
(3)	STATE $E_1 = E_2$ or $PE_1 + KE_1 = PE_2 + KE_2$
(4)	STATE $PE_1 = mgh$, $PE_2 = 0$, $KE_1 = 0$, $KE_2 = \frac{1}{2}mv_b^2 + \frac{1}{2}Iw^2$ $v_b = wr$, $\frac{1}{2}Iw^2 = \frac{1}{2}kmv_b^2$.
(5)	STATE $mgh + 0 = 0 + \frac{1}{2}mv_b^2 + \frac{1}{2}kmv_b^2$.
(5')	STATE $v_b^2 = 2gh/(1 + k)$

INSTRUMENTS

Table 2 gives an example of what the instruments for measuring the basic skills might look like. Each problem to be investigated must be broken down into the logical steps expected from the student. The student's work is then matched to the steps on the template for each problem. It is not the student's work that is scored but the template, so that each item on the template receives either a correct score or an incorrect score. The work can be correct in two ways: the work can be done explicitly as expected or it can be bypassed and done in the student's head. It can also be incorrect in two ways: the work can be done incorrectly using some unexpected content or it can be work remaining to be done.

Eleven problems in all where selected for the investigation out of 59 examination questions. The templates are given elsewhere.[15] The questions chosen were based on problems going beyond the mere illustration of those principles occuring the most frequently on the homework and examination questions. The three laws that occured the most frequently out of the eleven covered in the semester were $F=ma$, $E_1=E_2$, and $\tau=I\alpha$.

RELIABILITY

The scoring of the templates is at least 80% reliable. This was checked in two ways. One test of the reliability involved a check on the self-consistency of the author's scoring six months after the initial work. Four students, selected at random, had all eleven of their problems rescored. The results indicate better than 89% self-consistency with discrepancies

spread uniformly over each skill and all the examination questions. A second test of the reliability checked the agreement between other graders and the author's work. When these had received some training they were able to agree about 85% of the time on the scores assigned on the templates. A less well trained grader agreed only 56% of the ime. Thus the overall reliability is over 80%.

VALIDITY

By validity is meant that the questions chosen are actually representative of the type of questions in problem solving courses. Ten of the eleven problems were hard questions, sometimes giving even the staff members difficulties in getting them correct. Thus they are likely to contain quite a few problems that go beyond the mere illustration of principles. Furthermore, the derivation of equations suitable to a problem from underlying principles is typical of the kinds of questions asked on examinations.. In the course investigated 95% of the 39 examination questions invoved this kind of derivation. Thus the eleven questions chosen for investigation are definitely representative of problem solving tasks. The sample of questions should therefore be valid for investigating what makes problem solving on examinations hard for students.

COURSE AND INSTRUCTION

The course selected for investigation is rather typical of courses of its kind, a calculus based introductory physics course for students of science and engineering. The principles of mechanics and heat are covered in a five hour one semester course. Two one hour lectures, two one hour recitations, and one two hour laboratory are scheduled each week for about fifteen weeks. These are taught by experienced staff members having more than an average of ten years teaching experience and whose responsibilities are divided equally between teaching and research. The use of graduate students and research associates might be more typical of larger institutions. The laboratory instructors, as is typical of courses of this kind, are taught by graduate students.

The textbook, Elements of Physics, by Shortly and Williams[16] covers typical topics and contains quite typical problems solved in courses of this kind. In all about 250 homework problems were assigned to average about eight problems per recitation. While the popularity of textbooks at this level may differ considerably, the content and treatments are very similar with only minor variations between this text and some of the more commonly used textbooks.

STUDENTS AND SUBGROUPS

Not all the students in the class were chosen to take part in the study but only those volunteers (95%) who took all eight of the hourly examinations (58%). This left only about 40 students, since some of the examinations were optional repeated materials examinations which could be used to replace a previous lower examination score. Thirty two of these students whose average course grade and grade point average matched that of the whole class were chosen to take part in the investigation. When Natural Science aptitudes and Mathematics aptitudes were checked, the sample was found to be 11 percentile points below that of the whole class. This average is probably closer to what one would expect for an average

class of engineering students. Specifically the sample's Natural Science aptitude is 27.1 (57th percentile) and its Mathematics aptitude is 27.8 (65th) percentile. The percentile scores are based on ACT data for engineering students, not the general college population. Thus it is likely that the sample is itself a fairly representative group of engineering students.

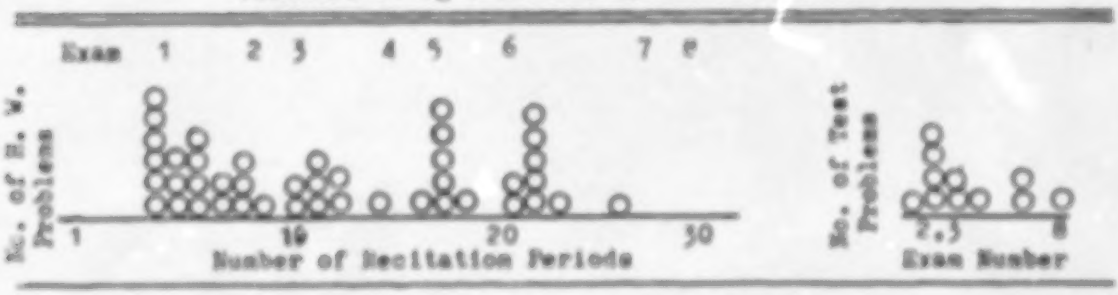
In order to increase the generality of the findings, this sample was divided into an upper and lower half of sixteen students each, and these were further divided on the basis of how much improvement they had made on the eight hourly examinations. The natural Science aptitudes of these subgroups ranged from 24.8 (44th percentile) to 29.5 (75rd percentile) while their Mathematics aptitudes ranged from 31.5 (92nd percentile) to 25.1 (41st percentile). These subgroups should show extremes in what might be expected from college classes.

VARIABLES

The dependent variable is the number of students successful on each of the skills, measured as a percentage. Thus the dependent variable is the probability of success on the specified tasks. Two independent variables have been considered. The first of these is the time, measured by the order in which six of the eight examinations were given. While this independent variable simplifies the analysis it also leads to the impression that performance is deteriorating throughout the semester. The second independent variable is the number of practice problems on which specific content appears. By analysing the homework problems for the content to be used in solving them, one determines the values of this variable. Figure 1 shows the results for the use of F=ma on the homework and test questions.

Figure 1

Practice Using F=ma on Homework and Tests



RESULTS

Figures 2a-2e show how well students perform each of the skills as a function of time. Figure 2a shows, for example, that skill (2) is virtually mastered by all of the students. The next skill, number (3), is at a much lower level of performance. It also shows a peculiar downward trend that gives the erroneous impression that the skill deteriorates with use. The downward trend of the line might actually be explained by the examination questions becoming harder as the course progresses. Skill (4) is not much below skill (3), however, skill (5) is considerably below skill (4), indicating that this skill is also a source of difficulty to the students. Skill (5') also appears to be considerably below (5) giving the impression that solution skills are not learned.

Figure 2a

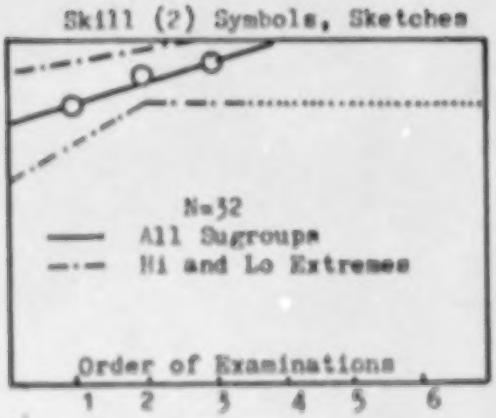


Figure 2b

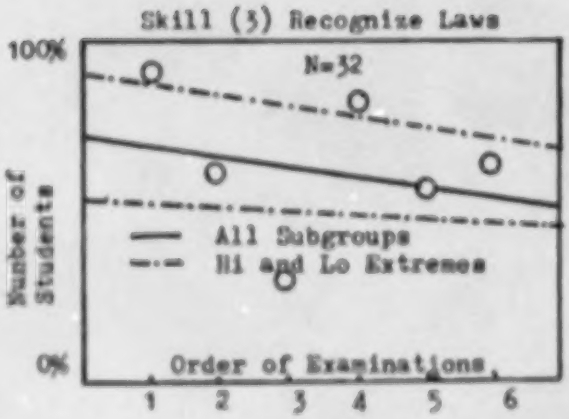


Figure 2c

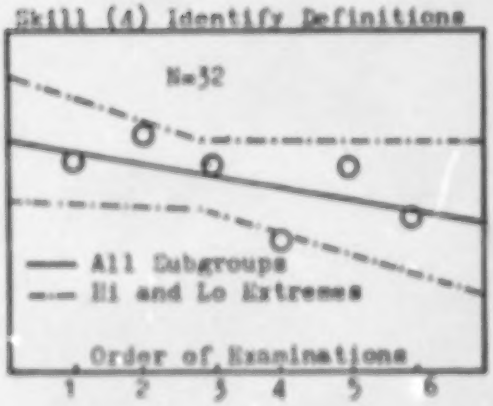


Figure 2d

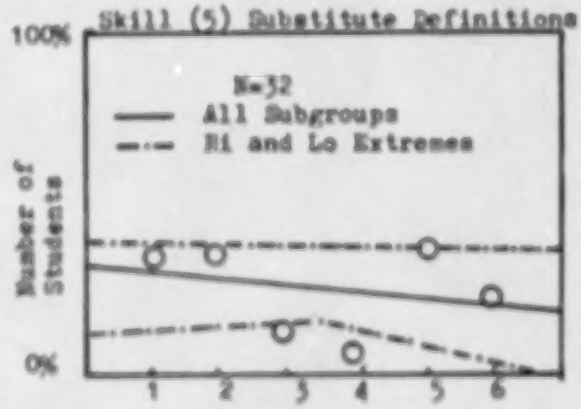
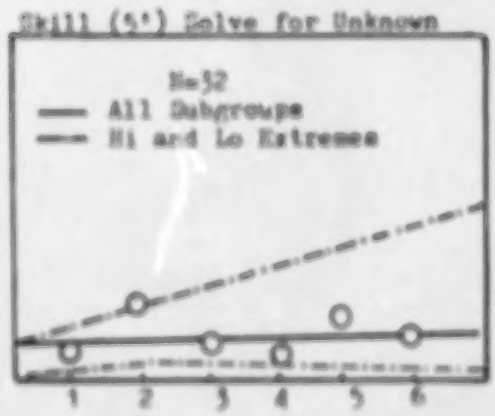


Figure 2e



100%

Number of Students

0%

Figures 2a-2e show the number of successful students on each of the skills as a function of time. No distinction is made between different content to which the skill must be applied. The result is that some of the lines show a downward trend, giving the misleading impression that the skills are not learned. Despite this impression one can still see which skills are especially hard for the students; namely, skill (5) and skill (5') which are at much lower levels than the preceding skills.

Figure 3 shows performance on skill (3) as a function of practice. This shows the expected upward trend in performance. The straight line imposed through the data is weighted to discount the points of initial high performance when students have had little practice. These initial points are thought to be high because either the questions might have been easier in the beginning or students expected a question on that content. On subsequent questions the students would not necessarily expect such a question and their performance would be directly indicative of how well they had learned the skill. The straight line imposed through this data is expected to indicate how successfully they could perform the given skill with increasing practice. (Only the three most practiced laws are included in the data: $F=ma$, $E_1=E_2$, and $t=l\alpha$.)

Figure 3

Skill (3): Recognize Laws

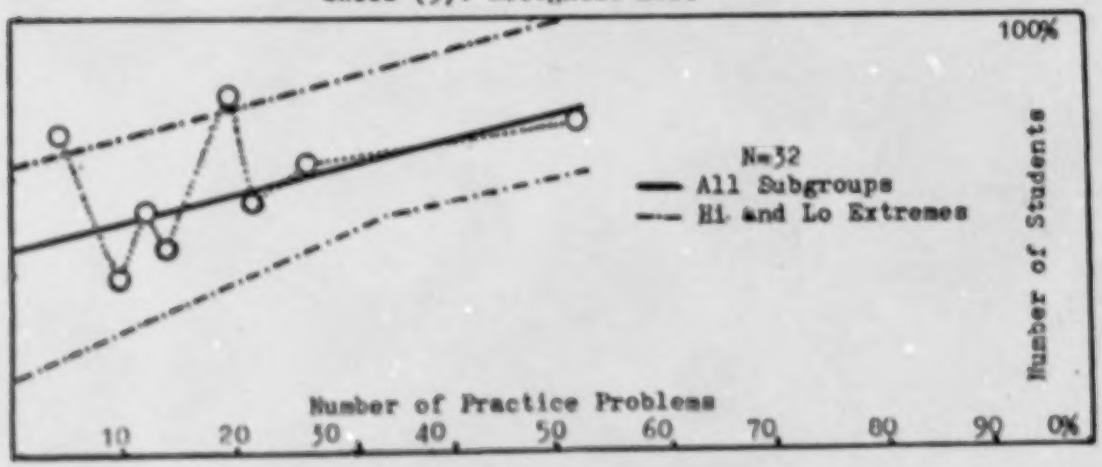


Table 3

Skill (3): Recognize Laws

Practice	5	10	12	14	20	22	27	53
Performance	75%	41%	57%	47%	83%	57%	66%	75%

The dashed lines indicate the expected rate of success for the various subgroups. None of these shows an initial performance higher than 66% while some subgoups are way below that. While improvement is found among all the groups, the rate of improvement is a very gradual one. The rate is so gradual that even after 50 practice problems only one of the subgroups appears to have mastered the skill. The median number of practice problems is only 13. With so little practice all the groups are far from mastery performance. This is evidently a skill that cannot be mastered in courses of this kind. Thus expecting students to perform this skill successfully is an unattainable goal and therefore is likely to discourage students giving rise to the feeling that physics is hard.

There were 11 laws covered in the present course. Cutting back to just two laws would still not guarantee mastery of this skill. It would probably improve performance and therefore lessen dissatisfaction, but it would not necessarily make even this limited goal attainable.

Figure 4 shows performance on skill (4) as a function of practice. This skill shows an overall upward trend as expected. However, there are two straight lines imposed on the data. The first line is imposed on the steep rapid rise during the first few practice problems. The second line is nearly a horizontal curve indicating a ceiling past which performance does not rise. Such a ceiling is expected from the level of performance of the previous skill. The ceiling actually exceeds the level of performance of the previous skill. This probably occurs because students are able to identify some of the four or so defining equations needed for a problem even if they are unable to identify all of them without the correct law.

Figure 4

Skill (4): Identify Definitions

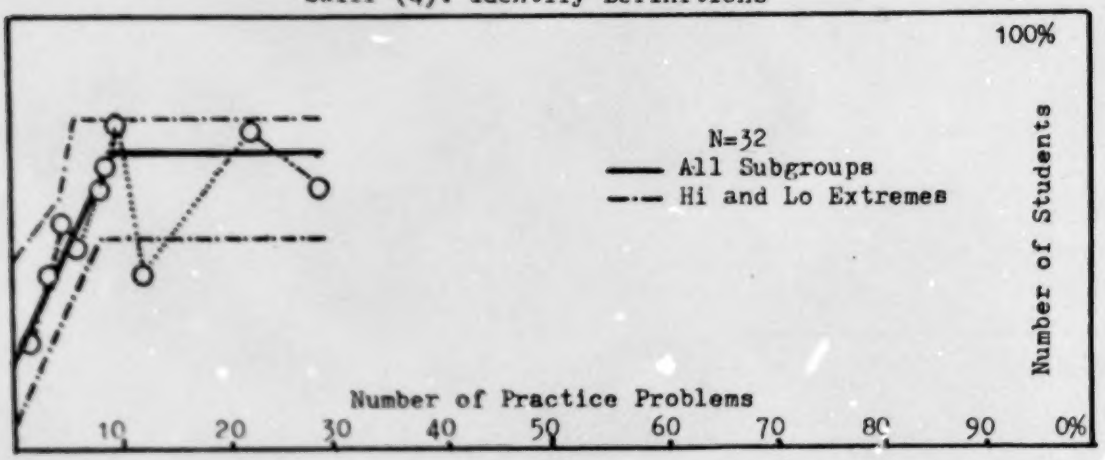


Table 4

Skill (4): Identify Definitions

Practice	1	3	5	6	8	9	11	12	23	30
Performance	25%	41%	50%	47%	60%	63%	74%	41%	71%	60%

The dashed lines indicate the extremes in performance by the various subgroups. All the subgoups follow the same pattern of reaching a ceiling imposed by the lack of mastery of the previous skill, and all reach this ceiling rapidly after a few practice problems. This indicates that mastery of this skill is reached within the time and practice available in the course. In fact, it is reached after about the median number of practice problems (median = 10).

It has been assumed the ceiling is due to the lack of mastery of the previous skill, since there is no indication in the student's work that the present skill is giving them some kind of insurmountable difficulty. Student's neither forget these definitions nor tend to confuse them with other definitions to such a noticible extent. It is more sensible to suppose that students could still identify these definitions but are unable to see that they are needed without the correct law to guide them.

Figure 5 shows performance on skill (5) as a function of practice. The data shows a clear upward trend upon which are imposed two straight lines. The first straight line is imposed on the rapid rise from virtually zero performance with no practice to a ceiling of about 35%. One expects such a ceiling from the lack of total success on the previous two skills. This particular ceiling is, however, considerably lower than either one of the previous skills. This indicates that the present skill is also a source of considerable difficulty to the student.

Figure 5

Skill (5): Substitute Definitions into the Laws

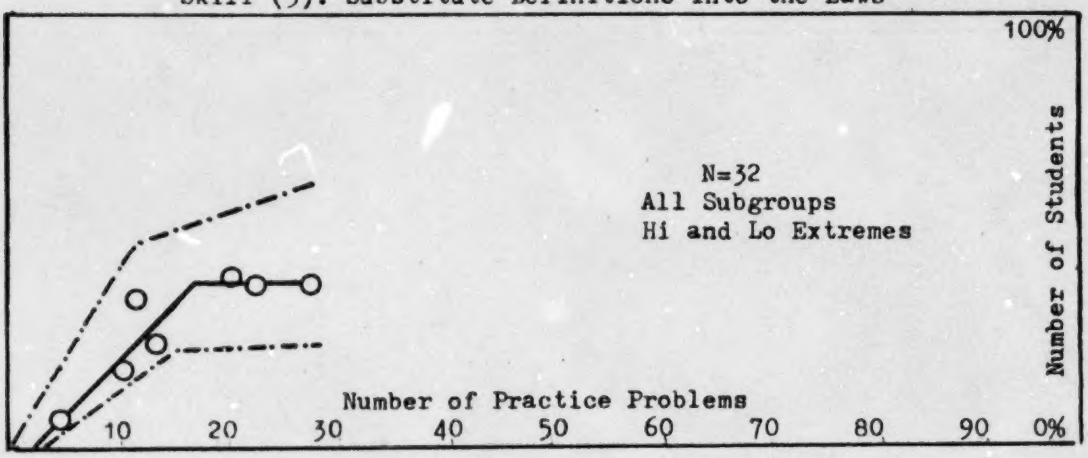


Table 5

Skill (5): Substitute Definitions into the Laws

Practice	5	10	12	14	19	22	27
Performance	7%	19%	35%	24%	40%	39%	38%

The dashed lines indicate the performance of the various subgroups. All the subgroups follow the same pattern of a rapid rise in performance from initial total failure without any practice. All the subgroups show a ceiling which is considerably below the ceiling imposed on the previous skill. Thus all the subgoups are having difficulty with this skill.

The mere act of substituting a definition into a law is not likely to be the source of the students' difficulties. Nor are there this many difficulties with individual definitions. On this skill, however, they are responsible for substituting all of the definitions correctly. Some of the failure is due to not knowing what law to use. The rest of the failure must be due to a lack of precise knowledge of one or another of the definitions the student must use. According to the work of Reif, Larkin, and Brackett[17] shortcomings of the latter kind can be corrected by practice in understanding the uses of each definition. The student can be taught certain study skills to acquire this skill on his own according to their findings. Thus poor showing on this skill can be attributed to a lack of proper study habits which do not permit students to learn as much as they might from existing materials.

Figure 6 shows performance on skill (5') as a function of practice. This skill shows an expected upward trend. Two straight lines are imposed on this data. The first line indicates the fairly rapid rise from zero performance with no practice to about 28% successful performance after nearly 20 practice problems. A second straight line has been imposed at this level indicating that there is a ceiling past which one does not expect performance to rise. Such a ceiling is to be expected from the lack of performance on the previous skills. At 28% it is only slightly less than the ceiling on the previous skill. Thus contrary to the indications in Figure 2e this skill does not represent an insurmountable difficulty, since students appear to master the skill when given enough practice.

Figure 6

Skill (5'): Solve for the Unknown

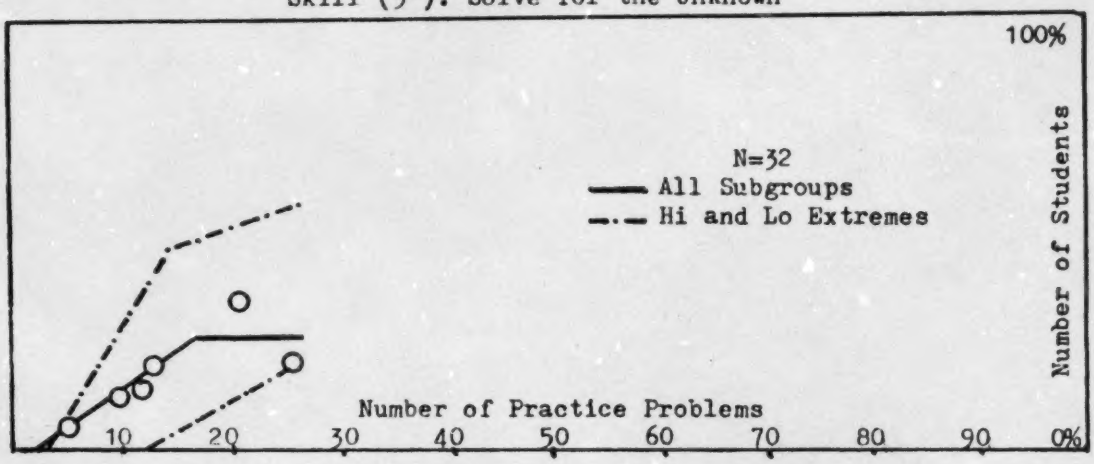


Table 6

Skill (5'): Solve for the Unknown

Practice	5	10	12	14	22	27
Performance	6%	13%	16%	19%	35%	21%

The dashed lines indicate the extremes in performance of the various subgroups. One of the lower half subgroups follows a slightly different pattern in that performance remains zero despite several practice problems before the group begins to show improvement. This group appears to be discouraged too easily and then does not do what little could still be carried out correctly. Most of the subgroups follow a pattern of a rapid initial rise without this delay period due to discouragement. The ceiling reached by these groups is not very different from the ceiling of the previous skill and thus indicates that the skill in question can be learned using the practice problems in the course.

This skill requires the use of mathematical tricks: elimination of unwanted common variables, integrations, differentiations, as well as algebraic manipulations. This skill can be learned in courses of this kind with existing materials, but about 20 practice problems are required for each kind of physics content.

Figure 7 shows the lines imposed on the skills (3) -(5). Skill (2) is not included, but is assumed to be very near performance that is 100% successful. Thus skill (3) represents a large drop in performance below that of the previous skill. There is also one other large drop shown by skill (5) below the levels of the previous skills. The remaining skills are very close to their theoretical ceilings and thus do not represent skills that were too hard to learn. Thus there are two skills that make problem solving in physics effectively so difficult with only about 15% chance of success in deriving the necessary equations (see Table 7).

Figure 7

Performance on Each Skill

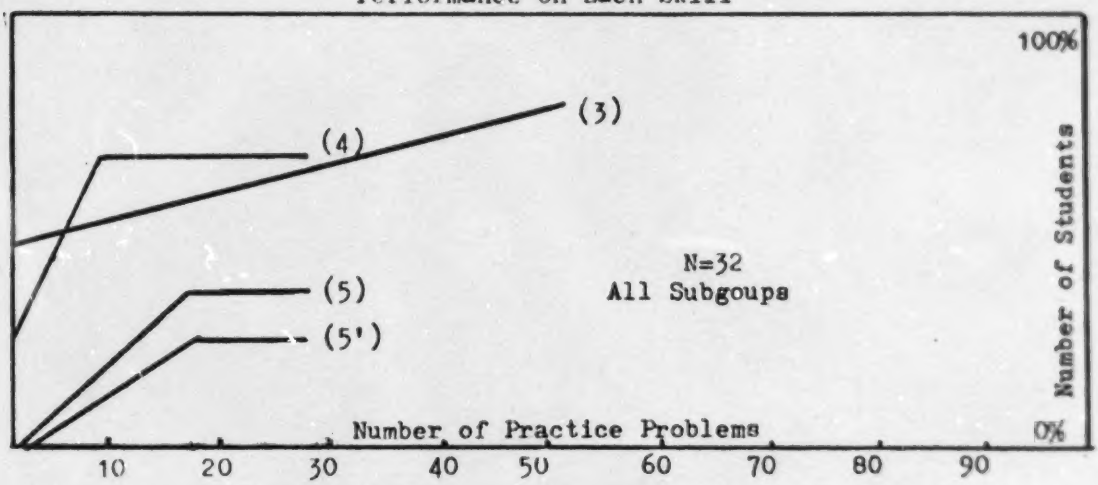


Table 7

Performance after Median Number of Practice Problems

Skill	low performance	median performance	high performance
(1)	100% est.	100% est.	100% est.
(2)	75%	93%	100%
(3)	32%	55%	75%
(4)	50%	65%	78%
(5)	15%	18%	48%
(5')	0%	15%	28%

CONCLUSIONS

The learning of basic problem solving skills was investigated in this study in order to determine if any of these skills contributed to making physics an unusually difficult subject. Four of the skills were found to be learned as well as could be expected, near their theoretical ceilings. The two remaining skills were considerably below the ceilings imposed by their antecedent skills.

FOOTNOTES

[1]A. A. Strassenburg, "Letters to the Editor," (A reply to Sister Pieta Shukivat), AAPT Announcer, 9, n1, Spring 1979, p 26.

[2]Yugal K. Behl, "Is Physics Hard to Learn? Part I," Contributed paper, AAPT Summer Meeting, Las Cruces, New Mexico, June 1979.

[3]A. E. Casewell, "The Content of the First Year Course in College Physics," American Physics Teacher, 1, 1933, p 95.

[4]James Gerhart, "Editorial: The Consumer Revolt and Physics," The Physics Teacher, 17, n2, 1979, p 83.

[5]Behl, "Is Physics Hard to Learn? Part II," op. cit.

[6]J. M. Fowler, "Content and Process in Physics Teaching," American Journal of Physics, 37, 1969, p 1194.

[7]Mary B. Rowe and Linda DeTure, A Summary of Research in Science Education: 1973, Interscience, John Wiley & Sons, New York, 1975, p55.

[8]Gerhart, op. cit., p 144.

[9]Casewell, op. cit., p 96.

[10]V. A. Krutetskii, The Psychology of Mathematical Abilities in Schoolchildren, U. of Chicago Press, Chicago, 1976, pp 50-51.

[11]G. P. Shchedrovitskii and S. G. Yakobson, "An Analysis of the Process of Solving Simple Arithmetic Problems," Soviet Studies in the Psychology of Learning and Teaching Mathematics, XIII, Stanford U., 1975, p 57.

[12]Allen Newell and Herbert A. Simon, Human Problem Solving, Prentice-Hall, Englewood Cliffs, New Jersey, 1972, p 94.

[13]Jill H. Larkin, "Problem Solving Processes of a Physics Student and a Physics Professor," Contributed paper, AAPT Winter Meeting, San Fransisco, Jan. 1978.

[14]Richard Hohly, Development of Basic Problem Solving Skills in Calculus Based Introductory Physics, Disseratation, Kansas State U., 1979 exp.

[15]Ibid., Appendix F.

[16]George Shortley and Dudley Williams, Elements of Physics for Students of Science and Engineering, 5th Ed., Prentice Hall, Englewood Cliffs, New Jersey, 1971.

[17]F. Reif, J. Larkin, and G. C. Brackett, "Teaching General Learning and Problem Solving Skills," American Journal of Physics, 44, n3, 1976, p 212.